

# **LOW-POWER-CONSUMPTION LASERS FOR NEXT-GENERATION MINIATURE SPECTROMETERS FOR VENUS AND MARS**

Director's Research and Development Fund (DRDF)  
Final Report

JPL Task #1326

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## **A. OBJECTIVES**

In situ detection of isotopic ratios of atmospheric trace gas species such as CO, CO<sub>2</sub>, H<sub>2</sub>O, H<sub>2</sub>O<sub>2</sub>, and NO have provided vital information about the formation and evolution of planetary bodies in our solar system. The presence and abundance of these chemicals are important indicators of geochemical processes, hydrothermal activity, and biological activity, if it exists. Measurements of these chemicals are of particular interest for the New Frontiers mission and Mars Exploration Program missions. The importance of trace gas detection was underscored by the selection of the tunable laser spectrometer (TLS) to be an instrument payload on the 2009 Mars Science Laboratory (MSL). Despite the remarkable instrument capabilities of TLS, the performance of next-generation tunable diode laser (TDL) spectrometers can be greatly improved by the development of mid-IR optical sources that require low electrical power to operate.

The objective of this task was to develop low-power quantum cascade (QC) semiconductor lasers operating in the 4.0–5.0- $\mu$ m wavelength range. In the report, we detail progress toward our goal.

## **B. APPROACH AND RESULTS**

### **1. Quantum design of 4.3- $\mu$ m quantum cascade lasers**

QC lasers were designed for emission near 4.3  $\mu$ m (around CO<sub>2</sub> absorption) and 4.6  $\mu$ m (around CO absorption) using the computational simulation tools developed at Princeton University. The design shown in Figure 1 as grown and fabricated emits near 4.6  $\mu$ m, with performance characteristics shown in Figure 2.

### **2. Growth of the lasers**

Laser growth was accomplished by metal organic chemical vapor deposition through resources available to Princeton University. Laser devices were fabricated and tested at

Princeton University. Figure 2(a) shows light-current-voltage measurements for some of the best-performing devices measured at Princeton. Lasers were also delivered to JPL for further testing and analysis. JPL confirmed results obtained by Princeton. Figure 2(b) shows emission from a laser operating in continuous wave (CW) mode near room temperature as measured by JPL. The laser emission is around 4.6  $\mu\text{m}$ , which is useful as it tunes over CO absorption lines.

### 3. Quality control of facet coatings

High-quality laser facet coatings are an integral part of our strategy toward achieving low-input-power QC lasers. By increasing the reflectivity of both laser facets, we decrease threshold current, thereby reducing input power required for laser operation. We have initiated development for the capability to apply robust and uniform infrared facet coatings at JPL. We modified an electron beam deposition system in the JPL Microdevices Lab (MDL) dedicated to dielectric materials to add the ability to deposit on semiconductor laser bars and to improve the quality and reproducibility of the coatings produced by the system. Specifically, we completed fabrication of fixtures to properly secure and align fragile semiconductor material during the dielectric deposition process. We also augmented the system with the capability to precisely monitor atomic and molecular compositions present in the vacuum atmosphere through the addition of a mass spectrometer. This has allowed us to increase quality and reproducibility of facet coatings by alerting us when atomic and molecular species detrimental to facet coating quality are present within the deposition system.

### 4. Characterization of the lasers

The ability to accurately measure performance characteristics is a crucial capability for a semiconductor. In this task, we assembled at JPL the necessary equipment to accomplish full characterization of QC lasers. This includes electrical and input/output power measurements with LIV (light-current-voltage) capability along with a Fourier transform infrared spectrometer (FTIR) for spectral characterization. We integrated and partially automated our equipment with the use of MATLAB programming and a control interface. The characterization setup assembled in this task is shown in Figure 3.

### 5. Laser packaging

Quality packaging of semiconductor laser bars is a crucial capability for achieving high-performance devices. Packaging is meant to mechanically secure the laser die to a standardized mount convenient for end-user deployment. Moreover, by efficiently removing waste heat that is generated during laser operation, a high-quality packaging process allows the laser device to achieve maximum operating temperature. We developed a complete packaging process — including dicing/cleaving of processed wafers, attaching laser die to mounts/submounts, and wire bonding electrical contacts — for our QC laser devices.

We designed our die attach process to provide a high degree of mechanical integrity while minimizing thermal resistance. Using a  $\text{Au}_{10}\text{Sn}_{90}$  fluxless solder preform, we achieved high-quality die attach to C-mount and TO-9 standardized packaging systems, as shown in Figures 4(a)–4(c). Figure 4(d) shows a bonding process that has yielded excellent facet

alignment with the edge of mounting surface and visual evidence of near 100% adhesion of the die to the attach medium. Destructive die shear tests, the results of which are shown in Figure 4(e) for multiple devices, indicate shear strength that exceeds Mil. Std. 883G (600 g force for a 1×1 mm die). Our current packaging process is finalized with wire bonding the laser die to the submount. Figures 4(a)–4(d) show multiple wire bonds from the laser die top contact to the laser package. The wire bonds are generally high quality, as most surpass Mil. Std. 883G with >3 g of force required for failure. The results of a series of destructive bond pull tests are shown in Figure 4(f).

### **C. SIGNIFICANCE OF RESULTS**

The primary objective of this task was to develop low-input-power QC lasers operating in the 4–5- $\mu\text{m}$  wavelength range. The completed tasks and accomplishments outlined above are progress toward that goal. We demonstrated room-temperature CW operation of QC lasers operating at 4.6  $\mu\text{m}$ , a wavelength useful for high-sensitivity CO detection. We also developed a foundation for fabricating high-performance QC lasers at JPL with the development of an advanced packaging process. With the test and characterization facility developed within this program, JPL is prepared for QC laser fabrication that can impact future space missions.

Measurements of chemical isotopes are just one area where this work will impact JPL missions and programs. Two methods are available for performing in situ measurements of isotopic ratios of atmospheric trace gases: isotope ratio mass spectrometry (IRMS) and tunable laser spectroscopy (TLS). The latter offers a much simpler method for isotope analysis since tunable laser spectrometers can be made much more compact than traditional IRMS instruments and chemical conversion is not required (e.g., IRMS requires methane to be oxidized to  $\text{CO}_2$ ). However, a fully robust and capable TLS system is not feasible if the laser source requires multi-watt input power for operation. Through the work done within this DRDF research, we have advanced our ability to produce low-input-power, mid-infrared laser sources.

### **D. FINANCIAL STATUS**

The total funding for this task was \$100,000, all of which has been expended.

### **E. ACKNOWLEDGEMENTS**

Collaborators on this project included: Richard Cendejas, Department of Electrical Engineering, Princeton University; Matthew D. Escarra, Department of Electrical Engineering, Princeton University; Loan Le, Department of Electrical Engineering, Princeton University; Arjun Vijayakumar, Department of Electrical Engineering, Princeton University; Kale J. Franz, Instrument Electronics and Sensors Section (389), and (formerly) Department of Electrical Engineering, Princeton University; Clifford Frez, Instrument Electronics and Sensors Section (389); and Yueming Qiu, Instrument Electronics and Sensors Section (389).

### **F. PUBLICATIONS**

None.

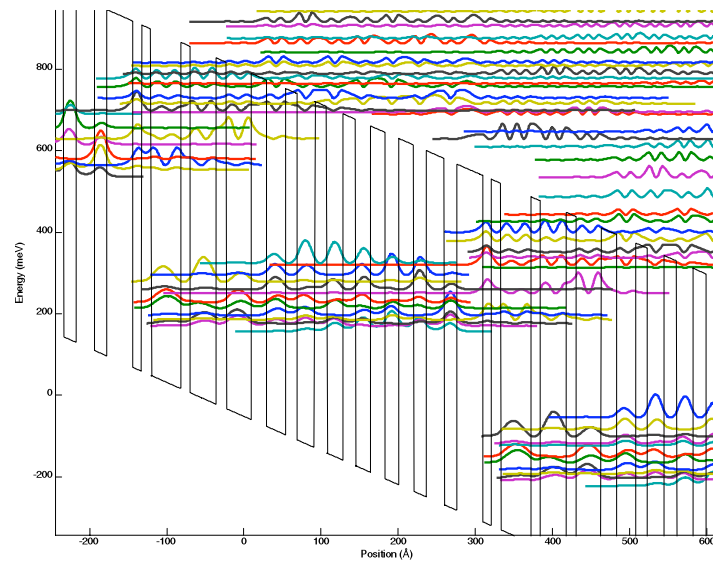
## G. REFERENCES

None.

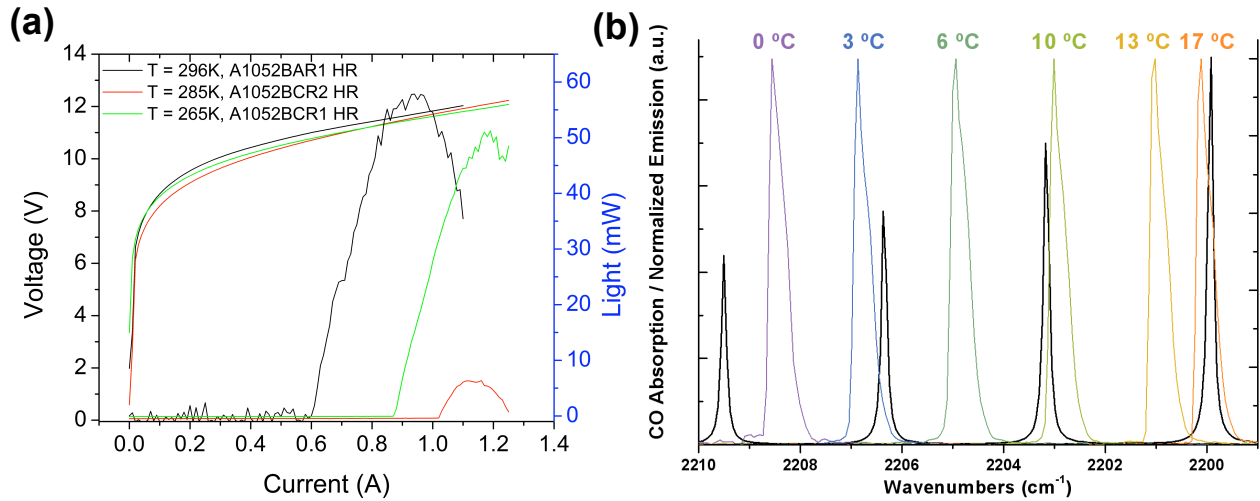
## H. APPENDIX: Noteworthy Ancillary Results of Princeton–JPL Collaboration

As a result of this collaboration between Princeton University and JPL, JPL was able to hire Kale Franz, a graduate of Prof. Claire Gmachl's research group at Princeton University. Dr. Franz brings with him to JPL advanced knowledge of QC laser operation, design, and fabrication. His skills augment JPL's ability to deliver a full spectrum of semiconductor laser devices for advanced space applications.

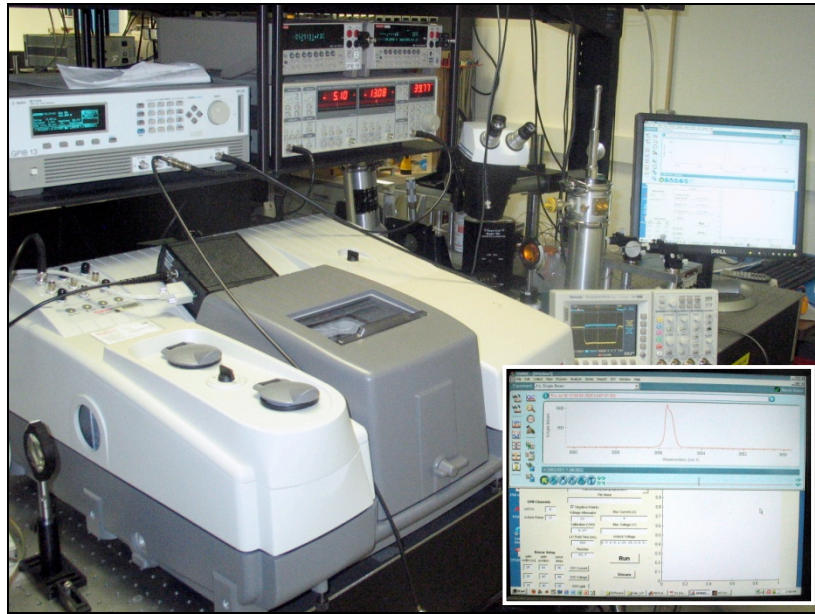
## I. FIGURES



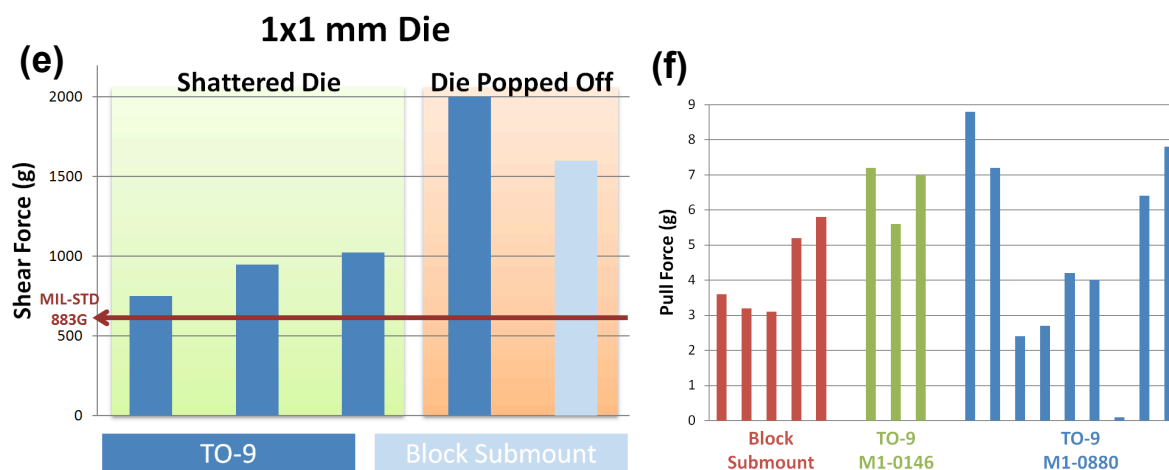
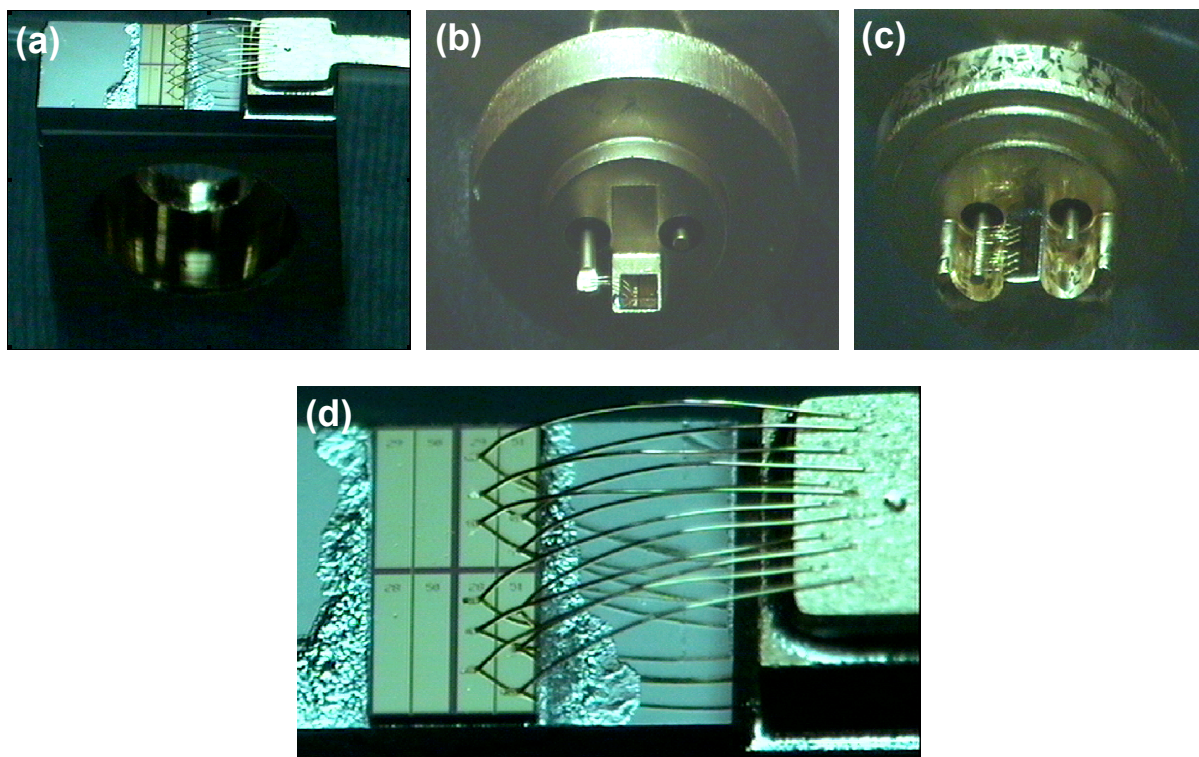
**Figure 1.** A QC laser structure designed and grown by Princeton University. As shown in the following figures, it is capable of room-temperature CW emission.



**Figure 2.** (a) Top performance achieved from several different laser ridges of the QC laser structure shown in Figure 1. The curves show voltage vs. current and light vs. current for three different lasers operating in CW mode. (b) Normalized emission of a QC laser operating in CW mode near room temperature. The laser operates above room temperature; however, this temperature region was chosen to show the laser's thermal wavelength turning over several CO absorption peaks, shown in the above figure with a bold black line.



**Figure 3.** The QC laser characterization setup assembled for characterization work at JPL. The system includes an FTIR, power sources, and temperature control, and is controlled through a customized MATLAB interface.



**Figure 4.** Packaging of laser die developed by JPL through this work. Panels (a)–(c) show laser die attached to a C-mount and two different TO-9 packages. Panel (d) shows in detail a high-quality die attach along with wire bonding of the laser top contact. Panels (e) and (f) show the results of destructive shear force and wire pull tests for several devices, respectively. The tests indicate a high-quality packaging process that passes Mil. Std. 883G.